Soil water retention curves representing tropical clay soils from Africa

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ABSTRACT: Soil water retention curves (SWRCs) form an essential component of frameworks coupling the hydromechanical behaviour of unsaturated soils. The curves describe how suction changes with variables such as degree of saturation, void ratio and volumetric/gravimetric water content. SWRCs can be determined from incrementally drying initially saturated reconstituted samples to a final residual state, thus developing the primary drying curve (PDC). The primary wetting curve (PWC) is established from subsequent incremental wetting from residual state and is hysteretic compared with the PDC. SWRCs for reconstituted, high-plasticity, tropical clays from Africa (Sudan and South Africa) will be produced using suction measuring instrument, a dew point potentiometer. The development of SWRCs under drying will be presented and discussed along with details concerning volumetric changes and cracking during drying. In order to investigate the uniqueness of the PDC and the effect of initial void ratio, SWRCs will determined for samples formed by consolidation under applied energy levels.

1 INTRODUCTION

Numerous researchers have proposed coupling the hydromechanical behaviour of unsaturated soils and several methods have been proposed to predict and estimate their engineering response. Soil suction constitutes an integral part of soil water retention curves (SWRC), which are frequently utilised to investigate the coupled hydromechanical behaviour of unsaturated soils. Fredlund et al. (2012); Chandler & Gutierrez, (1986) and Ridley et al., (2003) highlight the importance of SWRCs in understanding unsaturated soil behaviour. The SWRC is expressed as a relation between the logarithm of suction and either degree of saturation S_r, void ratio e, volumetric water content θ_w, or gravimetric water content, *w*. SWRCs generally have a sigmoidal form and plays a key role in recently proposed constitutive models and have been used to predict the compressibility during virgin loading (Wheeler et al., 2003), shear strength (Tarantino and Tombolato, 2005) and volume change behaviour of unsaturated soil. SWRCs are usually determined experimentally in the laboratory and can then be related to other properties of the unsaturated soil.

Data for developing SWRCs are often obtained by incrementally drying initially saturated, reconstituted samples to a final residual state, at which S_r remains constant, thus developing what is often referred to as the primary drying curve (PDC). The wetting-up process can then commence by adding small amounts of water to the sample in incremental stages.

Both drying and wetting curves can be drawn (generally as log s versus S_r) from these measurements. If drying starts from slurry, the two curves are considered to be boundary curves (primary drying curve PDC and primary wetting curve PWC) and it is often considered that any sample in any condition should lie within these boundaries. Usually, the end of the wetting curve differs from the starting point of the drying curve (i.e. the soil does not return to a fully saturated state). As the PWC does not follow the path of the PDC the process of drying and wetting is hysteretic. If small wetting and drying cycles take place from positions along the PDC or PWC, intermediate curves are created within the primary curves called scanning curves (Al Haj & Standing, 2016).

For very plastic clays, sometimes it is not possible to develop the full SWRC because of limitations of some suction measurement techniques, e.g. with the filter paper method the maximum suction that can be measured is -30 MPa. In these cases, it is not possible to reach the residual value because the soil has developed very high suctions while the degree of saturation is still relatively high. This is particularly the case for highly plastic clays (Al Haj & Standing, 2016).

Numerous formulations are available for mathematically modelling the sigmoidal form of SWRCs.

A comprehensive summary of these is given by Fredlund et al. (2012).

The model given by van Genuchten (1980) is commonly used, for which the residual point needs to be defined.

2 SOIL CHARACTERISTIC AND SAMPLES PREPARATION

The work presented here forms part of WindAfrica research project (http://community.dur.ac.uk/wind.africa/) which aims to develop new design guidelines for foundations of wind turbines on expansive soils. This paper presents the results of laboratory works conducted at Cambridge University on two natural soils from two locations in Africa: a black cotton clay from Sudan (Al Fao) and Atta clay from Steelpoort, South Africa (SA). One of the aims of the research was to generate SWRCs for the both of clay soils. Basic characteristics of the soils are given in Table 1.

Both soils were reconstituted from slurry in a consolidometer to a vertical total stress of 200 kPa (Al haj & Standing, 2015). Four discs for each soil were trimmed from the resulting soil cakes and initial water content and volume measured.

The discs were gradually dried, measuring total suction, in order to obtain the Soil-Water Retention Curve (SWRC) for each soil.

Table 1. Basic soil characterises

Soil type	Sudanese clay	South African clay
Gravel (%)	4	3
Sand (%)	7	9
Silt (%)	26	21
Clay (%)	63	67
Liquid limit, LL: %	60	92
Plastic limit, PL: %	30	37
Plasticity index, PI: %	30	55
Activity (PI/clay content)	0.63	0.80
BS classification	CH	CE

3 SUCTION AND VOLUME CHANGE MEASUREMENT

A dewpoint potentiometer (WP4C) was used to determined suction within the soil samples (Devices, D. , 2015). The WP4C uses the relative humidity of the air above a sample in a sealed chamber to measure water potential. Once the sample comes into equilibrium with the vapour, relative humidity is determined using the chilled mirror technique. At the dew point, the WP4C measures both mirror and sample temperature within 0.001 °C. The device can measure suction ranging between -0.1 MPa to -300 MPa with an accuracy of ±0.05 MPa from 0 to -5 MPa and 1% from -5 to -300 MPa.

After taking a set of measurement, the discs were dried in stages (incrementally), with a suction measurement made each time, to develop the PDC and PWC of SWRC for each soil. Ideally drying and associated measurement would be continued until the residual state was reached.

4 EXPERIMENTAL RESULTS

4.1 Laboratory SWRCs for Sudanese soil samples

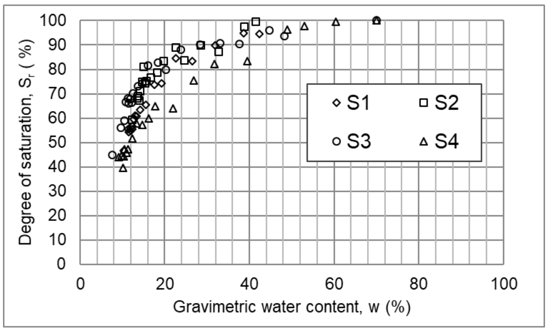
Results of the drying of the reconstituted Sudanese soil are presented in terms of: gravimetric water content and total suction in Figs 1(a)–1(f). In these figures the drying curve (first drying stage in Fig. 1) defines the PDC, which was continued to the -300 MPa limit of the WP4C device. From this point the sample will wet in small increments to low suction values, forming a PSC; at low suction values this curve will tend to converge to the PWC (Al Haj & Standing, 2016). The following observations can be made relating to the figures.

There is only one drying stage of four samples shown in Fig. 1, during which measurements were made to define PDC of the SWRCs for the Sudanese sample. Initially the sample was dried, establishing the PDC, which could only be extended to S_r=44% when the limit of the WP4C was reached (Figs 1(a) and 1(b)).

As suction measurements were not possible at the residual state, four independently prepared, reconstituted discs of both Sudanese and South African soil were prepared and left to dry under laboratory conditions in order to investigate the final water content and degree of saturation.

These samples started with gravimetric water contents of 70 and 114% respectively and eventually equilibrated at values of about 9% and 13% for the Sudanese and South African soils, respectively (corresponding to degrees of saturation of 44% and 59%). As these values are very similar to those at the limiting suctions that could be measured, this suggests that a clearly defined sigmoidal form with the associated final residual state would not be reached through simple air drying and that some form of artificial drying or control to reduce the ambient relative humidity around the samples would be necessary.

The PDC is well defined in all four representations of the SWRC plotted in terms of the logarithm of suction (Figs 1(b), 1(d) and 1(f)), with the data exhibiting little scatter (sample 4). In terms of degree of saturation, the sample remained almost saturated (i.e. S_r=91%) to suctions of about 2 MPa.



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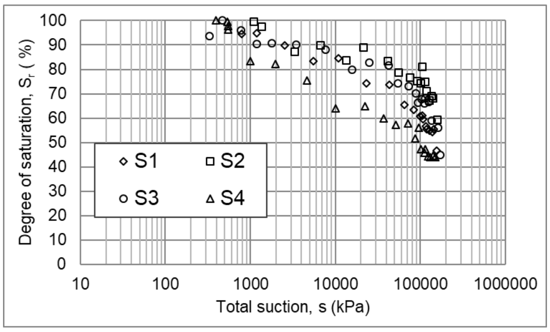

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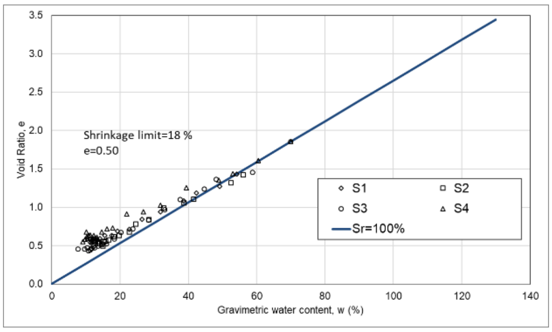

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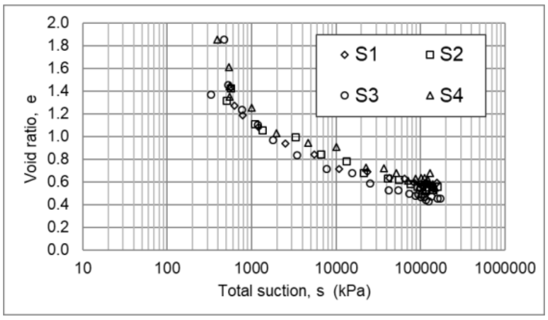

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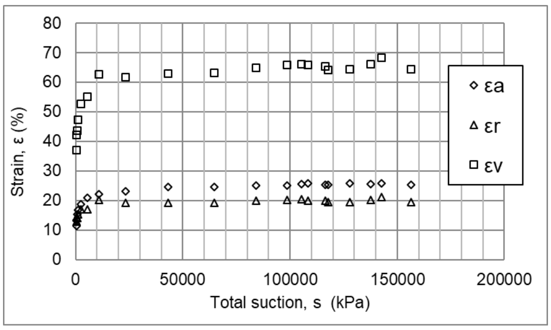

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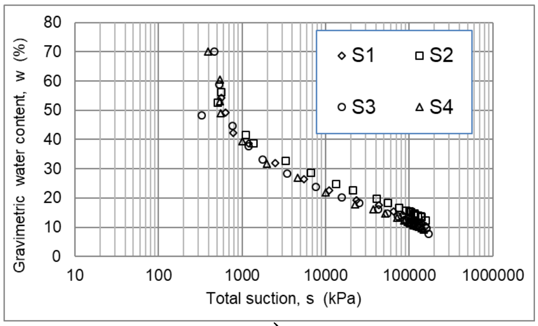


(f)

Figure 1. SWRCs for the phase of drying of a reconstituted sample of the Sudanese soil plotted in terms of: (a) w against S_r; (b) s against S_r; (c) w against e; (d) s against e; (e) s against ε; (f) s against w.

The data in these figures come from four sets of reconstituted samples; the reason for such large differences in these suction values is not clear, although it should be noted that the suction is not measured continuously and sometimes there are large steps between suction values.

Results from the first drying stage used to generate the PDC are plotted in terms of volume change, expressed as void ratio, e, against gravimetric water content in Fig. 1(c). The form of the data expressed in this way is often referred to as a shrinkage curve. There are three stages during drying of the Sudanese soil. The first is a saturated stage when any loss of water volume (ΔV_w) is equal to the reduction in overall volume (ΔV). A transition stage follows; linking saturated and shrinkage limit stages, when the loss of water volume is greater than the reduction in overall volume (ΔV, ΔV_w) and the sample becomes unsaturated. The third, shrinkage limit stage, corresponds to when the sample stops shrinking and the overall volume is not affected by any further loss of water: any loss of water volume is reflected by an equal change in air volume (ΔV_w=ΔV_a). It can be observed from Fig. 1(c) that the Sudanese soil has a clearly defined saturated stage at the start of drying: the saturation line (S_r=100%) drawn is based on the appropriate value of specific gravity, G_s=2.54. The Sudanese soil shrinkage curve diverges from the saturation line at a water content of 35.0% and void ratio of 1.00. The water content at the shrinkage limit is 18.0% and void ratio 0.50.

During the first drying, initially the form of the SWRC in terms of void ratio (Fig. 1(d)) is similar to compression curves from an oedometer test where effective stress is progressively increased by a corresponding application of total stress. When drying a sample to generate an SWRC, compression occurs due to progressively increasing suctions with no directly applied total stresses. These processes agree with the concepts of hydraulic and mechanical wetting suggested by Tarantino (2009). A marked change in compression is observed at about 2 MPa and towards the end of the measured PDC the void ratio becomes constant as the shrinkage limit is approached at e=0.50 (Figs 1(c) and 1(d)). Further loss of water does not cause any decrease in volume, as by this stage the soil particles are held in position by interparticle forces from water menisci.

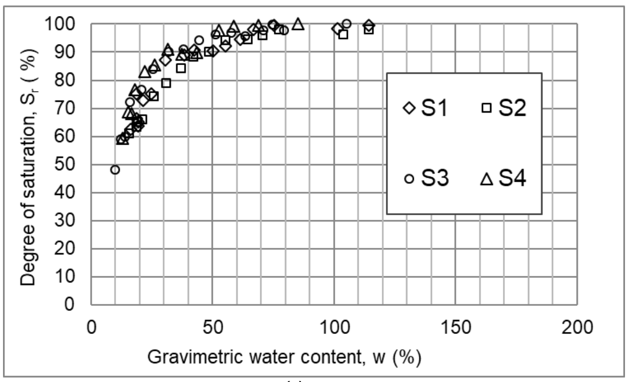
Axial, radial and volumetric strains (ε_a, ε_r and ε_v) that developed during the first drying of the black disc samples are plotted against total suction in Fig. 1(e).

Very rapid increases in strains are evident as suctions increase to about 2 MPa, with axial and radial strains reaching about 50 to 75% of their final values The paths shown in Fig. 1(e) are generally smooth, developing with increasing suction, albeit very gradually for the later stages of drying. Slightly greater axial than radial strains developed initially in the Sudanese sample, after which they tended to converge with increasing suction towards the shrinkage limit, reaching a limiting value of about 18%.

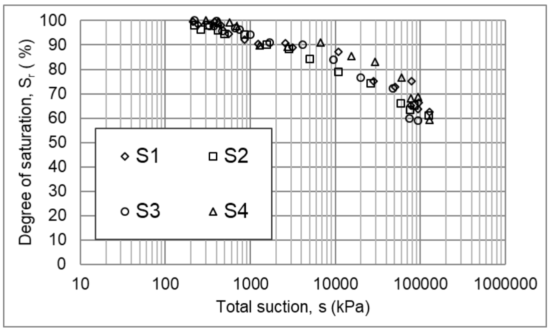
Changes in volumetric strain ($\varepsilon_v=\varepsilon_a+2\varepsilon_r$) take place quite rapidly up to a suction of about 2 MPa, as with axial and radial strains, as would be expected. The volumetric strain levels off at about 65% from a suction value of about 84 MPa, which corresponds to that observed at the shrinkage limit in Figs 1(c) and 1(d). Gravimetric water contents reduce steadily during the first drying from 70% to 9% at the limit of the dewpoint suction measurement. Although not shown, a similar response was observed in terms of volumetric water content (θ_w reducing from 75% to 16%).

4.2 Laboratory SWRCs for South African (SA) soil samples

Similar sets of plots to those discussed for the Sudanese soil are presented in Figs 2(a)–2(f) for SA soil samples. Trends in sample behaviour are generally very similar to those of the Sudanese soil. As the SA soil is more plastic with a greater fines content, greater suctions are generated at comparable stages and the degree of saturation was higher at the limit of the dewpoint method (S_r=59% compared with 44% for the Sudanese soil).



(a)



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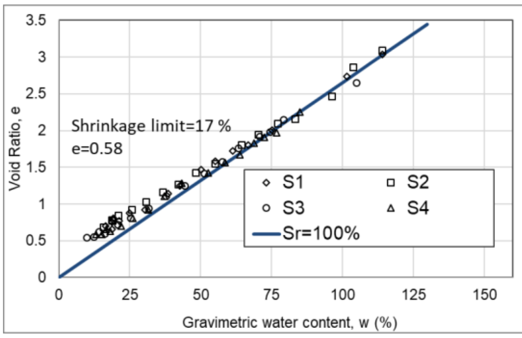

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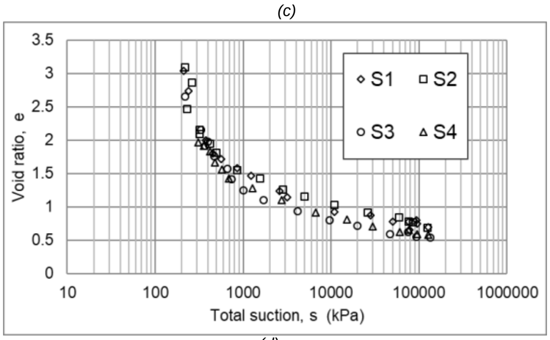

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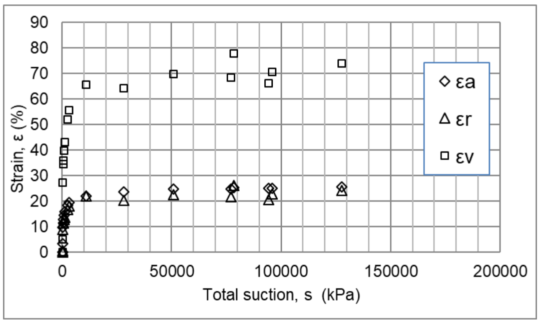

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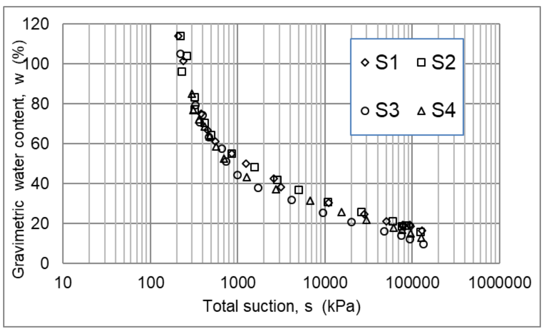

(f)

Figure 2. SWRCs for phase of drying of a reconstituted sample of the South African soil plotted in terms of: (a) w against S_r; (b) s against Sr; (c) w against e; (d) s against e; (e) s against ε; (f) s against w.

Differences between responses of the two soils are discussed below.

(a) One drying cycle was measured for the SA soil, the first drying path being the PDC and extending to the limiting suction of -300 MPa.

(b) The SA soil remained almost saturated to much higher total suctions (S_r=90% at s=7000 kPa). No cracking initiated while the sample was dried.

(c) The shrinkage curve for the SA soil (Fig. 2(c)) follows the saturation line (based on G_s=2.65) for a greater volume change than the Sudanese soil (void ratio reducing from 3.05 to 0.58, c.f. 1.85 to 0.50 for the Sudanese soil).

This is due to the greater fines content of the SA soil (Table 1), agreeing with the experimental results of Bronswijk (1988), who showed that soils with high clay content remain saturated over a wide range of water contents during desiccation. The SA soil remains saturated ($\Delta V=\Delta V_w$) until the shrinkage limit is reached (w=17.0% and e=0.58) with an abrupt transition.

(d) The SA soil has a higher initial void ratio than the Sudanese soil (e_0=3.05 c.f. e_0=1.85 for the Sudanese soil), decreasing steeply to 0·58 at the limit of the drying measurement (c.f. 0.50 for Sudanese soil). Again the shrinkage limit is fined (Figs 2(c) and 2(d)).

(e) Strains in the SA sample are greater than those of the Sudanese sample because of its greater fines content (Fig. 2(e)). Again sharp increases in strain occur up to about 100 MPa, representing about 80 to 95% of their final values. The initial dimensions of the Sudanese and SA samples were essentially the same at the start of the drying (diameter ~36 mm and height ~6 mm). However, the SA sample developed greater axial than radial strains initially, in contrast to the response of the Sudanese soil. Axial and radial strains converge at a suction value of about 100 MPa.

(f) The gravimetric water content of SA soil (Fig. 2(f)) starts at 114% and reduces to 13.0% (c.f. 70.0% and 9.0% for the Sudanese soil) and, although not shown, the volumetric water content has initial and final values of 75.0% and 17.0% (c.f. 75.0% and 16.0% for the Sudanese soil).

(g) Similar trends in total suction occur (Figs 2(a), 2(c) and 2(e)) as for the Sudanese soil.

5 CONCLUSIONS

Soil water retention curves provide an important conceptual means of describing the response of soils as they are dried and wetted. They are often expressed in terms of log suction plotted against the degree of saturation, but can also be plotted against void ratio or gravimetric/volumetric water content. An extensive set of SWRCs has been determined for two high-plasticity, tropical soils using reconstituted samples. Total suctions were measured using the dewpoint device technique, allowing drying to be continued to its limit of -300 MPa.

Having such a wide range of SWRCs has allowed the influence of initial void ratio and structure to be investigated. Observations on sample dimension changes have also been presented. The main conclusions from the study are as follows.

(a) For the reconstituted samples both Sudanese and SA soils show a clear first drying (PDC) (in terms of degree of saturation and volume change). Comparisons with the findings from microstructural studies (Romero et al., 2011) suggest that aggregations formed during the initial drying stage, similar to those observed with samples.

(b) The dewpoint limit meant that final suctions measured corresponded to degree of saturation values of only 44% and 59% for the reconstituted Sudanese and SA soils, respectively. In order to investigate this further, reconstituted samples were left to dry and equilibrate at a laboratory temperature. Final degree of saturation values were found to be similar to those at which the limit of the dewpoint technique was reached, suggesting that for high-plasticity clays the sigmoidal form of SWRC usually expected might not develop under moderate climatic temperatures.

(c) Shrinkage curves plotted for the Sudanese and SA soils (in terms of void ratio against water content) are slightly different, with the Sudanese soil following three stages of drying (fully saturated, partly saturated and shrinkage conditions) whereas for the SA soil petite intermediate stage between fully saturated and shrinkage conditions was observed (Fig. 1(c) and Fig. 2(c)). For both soils, the majority of volume changes occurred in the early stages of first drying, up to total suctions of 2 MPa for the Sudanese soil and 100 MPa for the SA soil (Fig. 1(e) and Fig. 2(e)).

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